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Charged-Particle Absorption by Io

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FOR THE COMMANDER

Jean Bogert

Jean Bogert, 1st Lt, USAF
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Deputy for Advanced Space Programs

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The electrostatic field associated with the rotation of Jupiter, relative to the rest frame of the satellite Io, would be distorted if the satellite were an electrical conductor (as the data on Jovian decametric radio emission may require). An idealized two-dimensional model of the distorted electric field configuration, in the limit of a perfectly conducting satellite or satellite ionosphere, has been constructed. This model has been used to trace the adiabatic guiding-center trajectories of energetic protons and electrons

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across Jupiter's magnetic-field lines, which are taken as rectilinear. The adiabatic trajectories of very low-energy particles (cold-plasma) are thus found to avoid the satellite and escape absorption. In the limit of very high particle energies the adiabatic trajectories are undistorted, and absorption proceeds as if Io were an insulator. The interpolation between these limits is monotonic for protons, such that (for example) Io sweeps out a drift shell half as wide as the satellite for first invariants $M \sim 1$ GeV/G (energies $\overline{W} \sim 20$ MeV). The situation for electrons is more complicated, and we find no absorption from adiabatic trajectories at $M \lesssim 46$ GeV/G ($\overline{W} \lesssim 30$ MeV). Electrons having $M \gtrsim 50$ GeV/G are typically swept out of drift shells wider than the satellite itself (by a factor ~ 1.5, for example, at $M \sim 400$ GeV/G, $\overline{W} \sim 90$ MeV). However, electrons can impact only a portion of Io's exposed hemisphere for $M \sim 50$-200 GeV/G ($\overline{W} \sim 30$-60 MeV). Thus, the particle-absorbing characteristics of an electrically conducting Jovian satellite are found to depend on both the species and the energy of the incident particle, and the satellite's particle-absorbing cross section differs systematically from its geometric cross section.

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CHARGED-PARTICLE ABSORPTION BY IO

The five inner satellites of Jupiter remain within the magnetosphere at all times. They execute nearly circular equatorial orbits about the planet. These facts have led Mead and Hess (1973) to predict a depletion of zenomagnetically trapped (charged-particle) radiation at drift shells that intersect the satellites. Subsequent quantitative analyses of particle absorption by Jovian satellites (Coroniti, 1974; Hess, Birmingham, and Mead, 1974; Thomsen and Goertz, 1975) have typically treated the satellites as electrical insulators that do not otherwise (apart from absorption) perturb the adiabatic trajectory of a charged particle. Such a treatment (which may well be valid for Europa, Ganymede, Callisto, and Amalthea) identifies the absorption cross section with the geometrical cross section.

However, the well-known correlation between the orbital phase of the satellite Io and the terrestrial observation of Jovian decametric radio bursts (Bigg, 1964) has led Piddington and Drake (1968) to propose that Io is a good electrical conductor. The detailed consequences of such a model for Io have been investigated by Goldreich and Lynden-Bell (1969). Whether the conductivity results mainly from Io's interior composition (Goldreich and Lynden-Bell, 1969), from its surface composition (Matson, Fanale, and Johnson, 1974), or from its ionosphere (Kliore, Fjeldbo, Seidel, Sweetnam, Sesplaukis, Woiceshyn, and Rasool, 1975) is uncertain, but is of little consequence to the present discussion.

CONTENTS

FIGURE

TABLES

The point is that a conducting Io must inevitably distort (in the vicinity of Io) the electrostatic field $\underset{\sim}{E}$ (= $-\underset{\sim}{\nabla}V$) associated with Jupiter's rotation, and must thereby alter the adiabatic trajectories of zenomagnetically trapped particles there. The purpose of the present work is to estimate the quantitative effect of this distortion on the ability of Io to absorb charged particles from the Jovian magnetosphere. Our intent is not to prejudge alternative radio-burst mechanisms which may not require Io to be a good conductor, but rather to derive some further consequences of those mechanisms that do require it (cf. Huba and Wu, 1976).

In order to make the present analysis tractable, we have adopted an idealized rectangular model in which

$$V(\underset{\sim}{r}) = (a_0^3 B_0/r_1^2 c)\, \underset{\sim}{\Omega} \cdot \underset{\sim}{\hat{B}} [1 - (a_1/r)^2] x \tag{1}$$

and

$$\underset{\sim}{B}(\underset{\sim}{r}) = -\underset{\sim}{\hat{z}} B_0 (a_0/r_1)^3 [1 - 3(x/r_1)], \tag{2}$$

where a_0 (= 71372 km) is the radius of Jupiter, a_1 (= 1930 km) is the radius of Io (including a substantial part of its ionosphere), and r_1 (= 421600 km) is the radius of Io's orbit (Blanco and McCuskey, 1961). Thus, Io and its flux tube constitute a cylinder (of radius $r = a_1$) that extends to $x = \pm\infty$, and the magnetic field $\underset{\sim}{B}$ is everywhere antiparallel to Jupiter's rotation axis ($\underset{\sim}{\hat{\Omega}} = \underset{\sim}{\hat{z}}$). The coordinates (x, y, z) originate at the center of Io. It proves convenient to introduce also the cylindrical coordinates (r, φ) such that

$x = r \cos \varphi$ and $y = r \sin \varphi$. The parameter B_0 (= 4.192 G, according to the spherical-harmonic analysis of Smith, Davis, Jones, Coleman, Colburn, Dyai, and Sonett, 1975) represents the equatorial dipolar magnetic-field intensity at the surface of Jupiter.

The geometry corresponding to (1) and (2) is illustrated in Figure 1a. Io and its flux tube constitute (by assumption) a perfectly conducting cylinder in which Jupiter's magnetic field is "frozen". The surrounding magnetospheric plasma flows (along equipotentials of V) around the flux tube as if the plasma were an incompressible fluid streaming without viscosity past a solid cylinder (Goldreich and Lynden-Bell, 1969). Guiding-center drift in the y direction here corresponds to azimuthal drift in the magnetosphere of Jupiter. Moreover, the absolute contributions of electric drift and gradient drift, as derived from (1) and (2), correspond at the orbit of Io to those obtaining in Jupiter's magnetosphere. Since the coordinates in Figure 1 are Iocentric, the angular velocity $\underset{\sim}{\Omega}$ in (1) must be assigned a magnitude (= 1.3467×10^{-4} $\sec^{-1}$) equal to the apparent rotation rate of Jupiter in the rest frame of Io (Blanco and McCuskey, 1961; Donivan and Carr, 1969; Mead and Hess, 1973).

Since the conductivity of Io and its flux tube is regarded as infinite in the present idealization, there is no perturbation of $\underset{\sim}{B}$ in Io's wake of the sort described by Goertz and Deift (1973). Moreover, the present model envisions no intrinsic magnetization or susceptibility for Io, as had been contemplated by Burns (1968). The flow velocity ($\Omega r_1 \sim 60$ km/sec) of Jovian plasma relative to Io is smaller than the Alfvén speed for a (hydrogen)

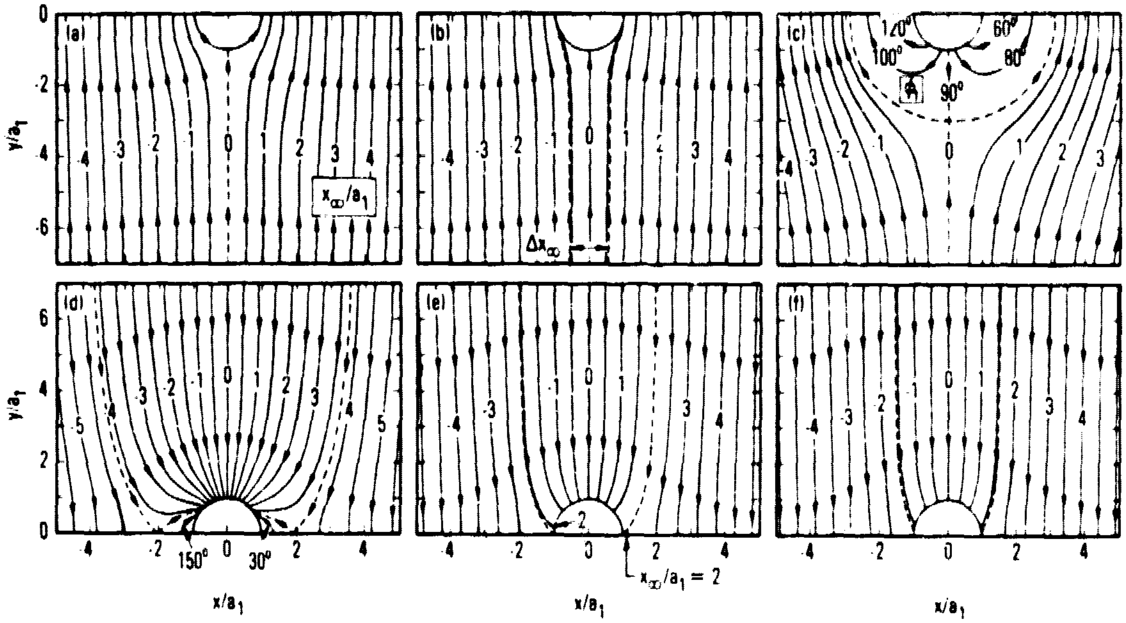

Figure 1. Drift paths of representative particles in the vicinity of Io: (a) particles having M = 0; (b) protons, M = 1 GeV/G; (c) electrons, M = 40 GeV/G; (d) electrons, M = 80 GeV/G; (e) electrons, M = 200 GeV/G; (f) electrons, M = 400 GeV/G. Dashed curves represent critical (grazing) trajectories and separatrices. Other trajectories are identified by values of x_∞/a_1 or of φ_1.

plasma density $N \lesssim 7 \times 10^5$ cm^{-3}; Io should have no standing bow shock in this case (Dryer, 1975). The flow would be subsonic only for a plasma temperature $T \gtrsim 10$ eV, but violation of this latter condition could only produce some electrostatic noise. It would not seriously alter the character of our simple model. We also ignore the possible effects of a photoelectric sheath (Gurnett, 1972; Hubbard, Shawhan, and Joyce, 1974) which might be present. The major weakness of the present model is our two-dimensional geometry, which makes Io's flux tube infinitely long, makes Io's orbit a straight line, and suppresses the curvature drift in Jupiter's magnetic field. However, the results obtained here should be reasonably valid for charged particles that mirror near (ideally at) Jupiter's magnetic equator.

For a particle with a vanishing component of velocity along $\underset{\sim}{B}$, conservation of the first adiabatic invariant M and total (kinetic plus potential) energy W imply a drift trajectory given (e.g., Schulz, 1972) by the equation

$$[1 + (2/m_0c^2)\,MB(\underset{\sim}{r})]^{1/2} + (q/m_0c^2)\,V(\underset{\sim}{r}) = [1 + (2/m_0c^2)\,MB_1]^{1/2}, \tag{3}$$

where q is the particle's charge and B_1 is the field intensity at the point $(r, \varpi) = (a_1, \varpi_1)$ where the trajectory intersects Io's flux tube. Since $V = 0$ at $r = a_1$, the right-hand side of (3) represents the conserved quantity $1 + (W/m_0c^2)$. The equipotential trajectories shown in Figure 1a correspond to $M = 0$ and are species-invariant. Trajectories for protons and electrons having other values of M are shown in the remaining panels of Figure 1.

Proton trajectories (see Figure 1b) that just graze Io's flux tube at $\varphi = 0$ and $\varphi = \pi$ are separated by a distance $2a_1$ there. These critical trajectories (dashed curves) attain a separation $\Delta x_\infty < 2a_1$ when mapped to $y = \pm\infty$. There are no stagnation points (intersecting trajectories) in the flow pattern (near Io, at least) for protons having $M > 0$ nor for electrons having $M > 205.2$ GeV/G. Critical trajectories of the latter (dashed curves, Figure 1f) just graze Io's flux tube at $\varphi = 0$ and $\varphi = \pi$ but attain a separation $\Delta x_\infty > 2a_1$ when mapped to $y = \pm\infty$. Individual trajectories can be labeled by x_∞ (the value of x at $y = \pm\infty$) or by φ_1 (the value of φ at $r = a_1$). Our interpretation of Figure 1 is that Io absorbs zenomagnetically trapped particles from drift shells (L, in the sense of Stone, 1963) having a bandwidth $\Delta L = \Delta x_\infty / a_0$, and that particles on drift shells outside this band avoid absorption. Representative values of $\Delta x_\infty / 2a_1$ are listed in Table 1. The symbol $\overline{W}$ denotes the (kinetic) energy of a particle on the trajectory $x = 0$ for given M. The $\mathbf{E} \times \mathbf{B}$ drift becomes negligible in the limit of large M, and so the ratio $\Delta x_\infty / 2a_1$ approaches unity for all charged-particle species in this limit.

The values of $\Delta x_\infty / 2a_1$ listed in Table 1 refer to guiding-center trajectories, and each might be augmented by the quantity

$$\overline{\rho}/a_1 \approx (2\, m_0 c^2\, r_1^3\, M / q^2\, B_0\, a_1^2\, a_0^3)^{1/2} \tag{4}$$

in order to account for the absorption of particles whose guiding centers pass within one gyration radius ($\bar{\rho}$) of Io ($r = a_1$) at $y = 0$. The sum $\Delta x_\infty^* \equiv \Delta x_\infty + 2\bar{\rho}$ is monotonic with M for protons, but not for electrons (which show a relative minimum in Δx_∞^* at $M \sim 2 \times 10^3$ GeV/G). However, protons having $M \gtrsim 10^2$ GeV/G and electrons having $M \gtrsim 3 \times 10^5$ GeV/G are found to execute guiding-center drifts $(2\pi \bar{\gamma} m_0 r_1^3 c / q B_0 a_0^3)\, \dot{y} \gtrsim 0.2 a_1$ during one gyration period. Thus, a particle with given M can (over a certain range of asymptotic impact parameters x_∞) either collide with Io or avoid Io, depending on the particle's gyrophase. In other words, the absorption process is somewhat probabilistic (rather than deterministic) for certain ranges of x_∞. However, the adiabatic approximation invoked in the present calculation of $\Delta x_\infty / 2a_1$ should be valid enough, since we find that $\bar{\rho}/a_1 \lesssim 0.3$ for $|(\Delta x_\infty/2a_1) - 1| \gtrsim 0.3$ and $3\bar{\rho}/r_1 \ll 1$ for $|(\Delta x_\infty/2a_1) - 1| \ll 1$. The distorted electric field and its characteristic scale length a_1 are important in the former contingency, but not in the latter.

Stagnation points in the flow pattern for electrons having $M \lesssim 200$ GeV/G generate the critical trajectories (dashed curves) in Figures 1c-1d. For $M \lesssim 46.38$ GeV/G the stagnation points occur only at $x=0$, with

$$y = \pm [1 - (3cM/q\bar{\gamma}\, r_1^2 \boldsymbol{\Omega} \cdot \hat{\mathbf{B}})]^{-1/2}\, a_1 \equiv \pm \Delta y/2, \qquad (5)$$

and generate a separatrix (dashed curve, Figure 1c) that precludes the adiabatic impact of such radiation-belt electrons with Io (hence, $\Delta x_\infty = 0$ in Table 1). The symbol $\bar{\gamma}$ ($\equiv [1 + (2MB_0/m_0c^2)(a_0/r_1)^3]^{1/2}$) denotes the particle's ratio of relativistic mass to rest mass at $x = 0$. The symbol γ denotes the same ratio in general, and stagnation points occur wherever

Table 1. Asymptotic bandwidths of drift shells intercepted by Io.

Invariant	Protons			Electrons		
M, GeV/G	$\overline{W}$, MeV	$\Delta x_{\infty}/2a_1$	$\overline{\rho}/a_1$	$\overline{W}$, MeV	$\Delta x_{\infty}/2a_1$	$\overline{\rho}/a_1$
0×10^0	0.00×10^0	0.0000	0.0000	0.00×10^0	0.0000	0.0000
1×10^0	2.01×10^1	0.5510	0.1602	4.08×10^0	0.0000	0.0037
2×10^0	3.98×10^1	0.7063	0.2266	5.96×10^0	0.0000	0.0053
5×10^0	9.67×10^1	0.8505	0.3583	9.70×10^0	0.0000	0.0084
[illegible] $\times 10^1$	1.85×10^2	0.9128	0.5067	1.39×10^1	0.0000	0.0118
2×10^1	3.44×10^2	0.9483	0.7165	1.99×10^1	0.0000	0.0167
5×10^1	7.32×10^2	0.9724	1.1330	3.17×10^1	3.6592	0.0264
1×10^2	1.23×10^3	0.9820	1.6023	4.51×10^1	3.1479	0.0374
2×10^2	1.98×10^3	0.9878	2.3461	6.40×10^1	2.0138	0.0548
5×10^2	3.53×10^3	0.9925	3.5827	1.01×10^2	1.4665	0.0836
1×10^3	5.31×10^3	0.9947	5.0668	1.44×10^2	1.2902	0.1182
2×10^3	7.85×10^3	0.9963	7.1655	2.03×10^2	1.1891	0.1672
5×10^3	1.29×10^4	0.9977	11.3296	3.22×10^2	1.1118	0.2644
1×10^4	1.86×10^4	0.9983	16.0225	4.55×10^2	1.0766	0.3739
1×10^5	6.08×10^4	0.9995	50.6677	1.44×10^3	1.0230	1.1825
1×10^6	1.94×10^5	0.9998	160.2254	4.56×10^3	1.0072	3.7393

$q\underset{\sim}{E} = (M/\gamma)\underset{\sim}{\nabla} B$. Thus, the stagnation points approach $y = \pm a_1$ (and the separatrix degenerates to the circle $r = a_1$) in the limit $M = 0$ (as illustrated in Figure 1a). The stagnation points specified by (5) recede to $y = \pm\infty$ as $M \rightarrow 50.70$ GeV/G, a limit in which the present rectangularized field model is not satisfactory.

The range of M values (46.38-59.74 GeV/G) spanning the complicated transition from the topology of Figure 1c to that of Figure 1d coincides roughly with the range over which the present model is too crude. Since the gradient and electric drifts nearly cancel at $|x/a_1| \lesssim 10$ for electrons in this range, a good description of the transitional drift trajectories would require a more accurate model of the variation of $\underset{\sim}{E}$ and $\underset{\sim}{B}$ with radial distance from Jupiter. We have formulated such a model and have found its consequences to agree well (within 1% for all values of $\Delta x_\infty/2a_1$ given in Table 1, although comparison was not feasible for electrons having $M = 50$-200 GeV/G) with those of the present model specified by (1) and (2). However, the more realistic model is too complicated for adequate description in the space available here, and it does not yield simple analytical criteria such as (5) for locating stagnation points in the flow pattern. Thus, we view the present (simplified) model as the more instructive, despite its failure over the range $M \approx 46$-60 GeV/G (corresponding to electron energies $\overline{W} \approx 30$-35 MeV at Io). We explore further consequences of the present model in this spirit.

For electrons having $M \gtrsim 60$ GeV/G the stagnation points appear at $y = 0$, with

$$x = \pm \left[(3cM/q\gamma r_1^2 \underset{\sim}{\Omega} \cdot \hat{\underset{\sim}{B}}) - 1 \right]^{-1/2} a_1, \qquad (6)$$

where $\gamma = [\bar{\gamma}^2 - 3(\bar{\gamma}^2 - 1)(x/r_1)]^{1/2}$. The iteration implicit in (6) converges quite rapidly, and the stagnation points thus specified generate separatrices of the type illustrated in Figure 1d. Electrons of this class can impact only a portion of Io's surface, i.e., the portion outside a pair of longitude intervals facing toward and away from Jupiter. The stagnation points approach $x = \pm a_1$ (exposing Io's entire surface to electron impact) for $M \sim 200$ GeV/G (as illustrated in Figure 1e). Actually, the outer stagnation point reaches $x = + a_1$ for $M = 199.6$ GeV/G, and the inner one reaches $x = - a_1$ for $M = 205.2$ GeV/G (above which there are no stagnation points in the electron-drift pattern near Io: see Figure 1f).

The results summarized in Table 1 correspond to the various adiabatic cases described above. These results suggest that Io's particle-absorbing cross section differs systematically from its geometric cross section, and in particular that Io cannot absorb electrons having $\overline{W} \lesssim 30$ MeV from Jupiter's radiation belt. This last conclusion seems to conflict with the observational data of Fillius and McIlwain (1974), which show depletions of the 160-keV and 9-MeV electron fluxes at the orbit of Io. One might hope to reconcile this conflict by appealing to collisional diffusion of electrons as they execute the curved portion of the separatrix (and nearby trajectories) in Figure 1c. However, such an effect turns out to be negligible; only particles on adiabatic trajectories that pass within ~ 1 km of the separatrix could conceivably experience a substantial ($\gtrsim 10\%$) probability of diffusing (by collisions) across the separatrix and (thus) onto trajectories that impact Io. Some alternative diffusion mechanism may be responsible for transporting such electrons ($\overline{W} \lesssim 30$ MeV) from a significant swath of drift shells across the separatrix to produce the observed absorption profile, but it is difficult to be quantitative about this.

The accepted global diffusion mechanism (Brice and McDonough, 1973) for Jupiter's magnetosphere involves fluctuating electric fields generated by fluctuations (perpendicular to $\mathbf{B}$) in the circulatory motion of Jupiter's neutral atmosphere at (Jovian) ionospheric altitudes. Hess et al. (1974) estimate the resulting radial-diffusion coefficient as $D \sim 300$ km^2/sec at the orbit of Io, and Coroniti (1974) estimates that $D \sim 250$ km^2/sec there. Spatial diffusion produces a mean-square displacement $\sim 2Dt$ after an interaction time t. The time required for an electron to execute the exact separatrix adiabatically turns out to be infinite because the particle is stationary at the points where $q\mathbf{E} = (M/\gamma)\nabla B$, as given by (5). However, a rough estimate for nearby paths is that

$$t \sim (\pi a_1/r_1\Omega)\,[\,1 - (3cM/q\gamma\, r_1^2\, \mathbf{\Omega}\cdot\hat{\mathbf{B}})]^{-3/2} \quad . \tag{7}$$

This represents a fraction $\Delta y/4r_1$ of the particle's full drift period $(2\pi/\Omega_3)$ between encounters with Io, where $\Delta y/2$ is the radius of the separatrix at $x = 0$, as given by (5). Representative values of $\Delta y/2a_1$, t, and $(2Dt)^{1/2}$, as derived from (5) and (7) with $D = 300$ km^2/sec, are given in Table 2. Thus, for example, electrons on adiabatic trajectories that pass within $\sim 10^3$ km of the separatrix at M = 20 GeV/G ($2Dt \sim 0.08\,a_1^2 \sim 3 \times 10^5$ km^2) should have a probability $\gtrsim 10\%$ of diffusing across the separatrix and being absorbed by Io on a given encounter. Tabulations of the full drift period $(2\pi/\Omega_3)$ between encounters with Io and the corresponding root-mean-square displacement $(4\pi D/\Omega_3)^{1/2}$ suggest that such an electron, if not absorbed on a given encounter with Io, has little chance of being absorbed on its next encounter (see Table 2).

The foregoing considerations (based on $D \sim 300\ km^2/sec$) apply only if Jupiter's radial-diffusion coefficient is unmodified in the vicinity of Io. This seems unlikely in view of the effect that Io's conductivity has on the adiabatic trajectories. An evaluation of Io's local effect on the magnitude of D would be interesting, but would exceed the intended scope of the present work. It would also be interesting to calculate the electrostatic potential $V(\underset{\sim}{r})$ surrounding an Io with only finite conductivity. Adiabatic particle trajectories in such a model would presumably lie between those calculated above and the simple trajectories postulated by Mead and Hess (1973) for the case of a perfectly insulating Io. However, the present work (even in the absence of such refinements) has demonstrated that the conductivity of Io entails a major reconsideration of the mechanism by which the satellite absorbs charged particles from the radiation belt of Jupiter. Conversely, if Io is observed to absorb charged particles in the manner of an insulating obstacle, then one must reconsider the electrodynamic aspects (Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969) of Io's interaction with the magnetosphere of Jupiter and the consequences of this for the theory of Jovian decametric radio emission.

Table 2. Dimensions of Separatrix, Drift and Diffusion Times, and Root-Mean-Square Displacements for Zenomagnetically Trapped Electrons at the Orbit of Io ($D = 300\ km^2/sec$).

Electrons		Dimensions of Separatrix				Time Scales		Displacements, km	
M	$\bar{Y}$	$\Delta y/2a_1$	$x/a_1(<0)$	$x/a_1(>0)$	$\Delta x/2a_1$	$2\pi/\Omega_3$, sec	t, sec	$(2Dt)^{1/2}$	$(4\pi D/\Omega_3)^{1/2}$
0	1.000	1.0000	-1.0000	1.0000	1.0000	46656	106.8	253.1	5290.9
1	8.978	1.0781	-1.0778	1.0784	1.0781	54426	133.8	283.3	5704.0
2	12.657	1.1167	-1.1161	1.1172	1.1167	58178	148.7	298.7	5908.2
5	19.975	1.2071	-1.2060	1.2083	1.2071	67984	187.8	335.7	6386.7
10	28.231	1.3410	-1.3386	1.3435	1.3411	83904	257.5	393.1	7095.3
20	39.912	1.6396	-1.6320	1.6476	1.6398	125426	470.7	531.4	8675.0
30	48.877	2.0817	-2.0580	2.1077	2.0828	202186	963.4	760.3	11014.2
40	56.436	2.9920	-2.8828	3.1319	3.0073	417655	2860	1310	15830
44	59.189	3.8253	-3.5484	4.2961	3.9223	682707	5978	1894	20239
48	61.821	6.0970	-4.8466	(open)	——	1734347	24203	3811	32258
50	63.095	12.1000	-6.1064	(open)	——	6830984	189190	10654	64020

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